MLS observations of Arctic ozone loss in 1996-97

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Abstract,. The Microwave Limb Sounder (M LS) observed ozone (O_3) decreases in the Arctic vortex beginning in Ja nuary 1997 at 585 K (~25 hPa) and in February 1997 at 465 K (~50 hPa). The minimum vortex-averaged O_3 mixing ratios observed in 1997 were higher than those in 1996, which were t he lowest ever recorded by M 1,S. The vertical extent of O_3 loss and maximum local O_3 decreases were larger, hut the decrease find the vortex less completely, in 1996-97 than in 1995-96. 111. S column O_3 above 100 hPa averaged in the low column O_3 region showed a stronger decreasing trend in 1996-97 than in 1995-96, consistent with the larger vertical extent of the lower stratospheric 03 decrease. Unusually low high-latitude col umn O_3 values in April 1997 resulted partly from chemical loss; however, dynamical effects related to the unusually persistent lower stratospheric vortex and winter-like temperature patterns also played a major role.

Introduction

While the Arctic lower stratosphere in 1995-96 winter was the coldest and most persistently cold of all northern hemisphere (NH) winters on record [*Manney et al.*, 1996, hereafter *M96*], the unprecedented persistence of temperatures below typical polar stratospheric cloud (PSC) thresholds into late Mar 1997 [*Coy et al.*, 1997, hereafter *C97*; *Santee et al.*, 1997, hereafter *S97*] raisin the possibility of chemical ozone (O_3) loss occurring later than in any previous year in which Arctic O_3 was observed. As shown by *Manney et al.* [1994], the NH lower stratospheric vortex typically breaks up in late March or early April. The 1997 vortex was intact and relatively strong into May (*C97* show diagnostics of vortex size and strength that confirm its remarkable persistence). In 1996-97, the Upper Atmosphere Research Satellite (UARS) Microwave Limb Sounder (MLS) observed the Arctic on selected days in December, late January, February and April. Although MLS did not observe the Arctic in Mar 1997, when temperatures were at record lows for that month [*C97*], the persistence of the vortex into nay continued to isolate air that had been chemically processed. Here, MLS observations of Arctic O_3 during 1996-97 are compared to those for 1995-96, when temperatures were colder overall [*M96*; *C97*] and chlorine activation greater than in 1996-97 [*S97*], and to earlier years with UARS data.

Data and Analysis

The MLS Version 3 O_3 data and validation are described by *Froidevaux et al.* [1996]. Version 4 data are used here; *M96* show some Version 3/4 differences in Arctic O_3. Precisions of individual O_3 measurements are ~0.2 ppmv, with absolute accuracies of 15-20% in the lower stratosphere. Due to UARS power limitations, and to conserve the lifetime of the MLS scan mechanism, MLS took full vertical scanning measurements only during selected parts of the north-looking periods in the 1996-97 winter.

Daily MLS data are gridded by a binning and averaging procedure, and interpolated to isentropic (potential temperature, θ) surfaces using United Kingdom Meteorological Office (UKMO) temperatures. Potential Vorticity (PV) is calculated from the UKMO analyses. Transport calculations are done using UKMO horizontal winds, diabatic descent rates computed from UKMO temperatures, and a reverse trajectory procedure [*M96* and references therein].

Results

Fig. 1 shows MLS maps of 465 K O_3 and column O_3 above 100 hPa ($ColO_3$) in late Jan, late Feb, and early and late Apr 1997. Fig. 2 shows 585 K and 465 K NH vortex-averaged MLS O_3, as well as $ColO_3$ averaged in the region north of 40°N with $ColO_3 \leq 250$ DU, during 1996-97 and 1995-96, with previous observations in the background; earlier winters are discussed by *M96*. Prior to 1997, the Arctic polar vortex had fragmented to such an extent in April that vortex averaging was no longer sensible [*Manney et al.*, 1994]. Also, no isolated regions of low $ColO_3$ in high latitudes remained. Thus, the points in Fig. 2 in April for years before 1997 are averages over small vortex remnants or small regions with $ColO_3 \leq 250$ DU, and are not fully comparable with the Apr 1997 averages.

Between late December and late January, vortex-averaged O_3 at 585 K decreased in both 1995-96 and 1996-97. Transport is expected to increase O_3 in the lower stratospheric vortex, through replenishment by diabatic descent. *M96* showed that the O_3 decrease at 585 K in 1995-96 was inconsistent with transport alone, and must have resulted from chemical loss. The decrease in 1996-97 suggests that chemical depletion began in Jan 1997 near 585 K. This is consistent with the evolution of temperatures and with chlorine activation, since, during Jan 1997, 585 K temperatures remained below the typical PSC threshold and MLS observed enhanced ClO at 585 K [*S97*]. 465 K vortex-averaged O_3 increased between late Dec 1996 and late Jan 1997, consistent with the behavior expected due to transport and the absence of temperatures low enough to form PSCs during most of this period [*C'97*; *S97*]. A year earlier, significant O_3 loss at 465 K had already occurred by late Jan 1996. Since O_3 continued to increase in Jan 1997 due to transport, 465 K O_3 in late Jan 1997 was higher than in late Jan 1996.

465 K vortex-averaged O_3 decreased rapidly during Feb 1997, at a rate slightly faster than that in Feb 1996. Most of this decrease occurred toward the vortex center (Fig. 1), consistent with HALOE observations [*Pierce et al.*, 1997]. Transport calculations at 465 K indicate that masking of chemical loss through replenishment via diabatic descent was less in Feb 1997 than in Feb 1996, with $\lesssim$10% of the loss masked, as compared to ~15% in 1996, and ~20-50% in previous NH winters [*M96*]. At 585 K, however, transport calculations suggest that ~75% of the chemical loss in Feb 1997 was masked by transport, an amount similar to other years [*M96*].

465 K temperatures remained low through most of Mar 1997 [*C97*; S97], so additional chemical O_3 loss was expected. Ground-based observations show O_3 in the polar vortex decreasing during Mar 1997 at levels between ~400 and ~520 K [*Donovan et al.*, 1997]. We used transport calculations to estimate the minimum value that MLS vortex-averaged O_3 may have reached during Mar 1997. The thin line in Fig. 2a and 2b starting from the data point on 26 Feb 1997 shows the expected behavior of O_3 due to transport alone, calculated from 26 Feb to 12 Apr 1997. While such calculations become more uncertain after ~20-25 days, trots using shorter calculations confirm that most of the O_3 change due to transport occurred before mid-March. The line ending at the 10 Apr 1997 data point shows how dynamical processes would have 1('(1 to that vortex-averaged O_3 value, based on the above calculation. The dots extending from the 26 Feb MLS observation are an extrapolation of the estimated slope of chemical loss for 20-26 Feb 1997 (calculated by combining the observed change with the increase due to transport over the late January-late February period, as described by *M96*). This line approximates the most rapid decrease likely to have occurred. The intersection

of the latter two lines thus gives a rough estimate of the lowest vortex-averaged O_3 value. At 585 K, minimum vortex-averaged O_3 mixing ratios in 1997 are estimated to be comparable to those in 1996, and at 465 K, minimum mixing ratios were probably slightly larger in 1997 than in 1 996. Vortex-averaged O_3 stayed nearly constant in Apr 1997 (Fig. 2a, 2b), with the low ozone mixing ratios resulting from chemical loss remaining confined within the vortex (Fig. 1).

Fig. 3 compares the spatial extent of O_3 loss observed by ~11.S during the 1996-97 and 1995-96 NH winters, showing changes over 69 days (chosen in each year so as to include the period of most rapid observed O_3 loss). '1'0 preserve the correlation with the vortex, O_3 changes are plotted as a function of equivalent latitude (PV expressed as the latitude that would encompass the same area as the PV contour) and θ [e.g., *M96*]. The maxi mum decline in 1997 was ~1 .5 ppmv, compared to ~1.1 ppmv in 1995-96. Although substant ial O_3 decreases in t he vortex extended somewhat higher in 199&9'i' t han in 199,5-96, differences over a shorter period in 1995-96 ending on 20 Feb 1996 (near the time of the minimum in Fig. 2a) show decreases near the vortex edge up to ~650 K, suggesting that some replenishment had already occurred by 3 Mar 1996. The large O_3 reductions in 1995-96 more completely filled the vortex at a given level than in 1997. The O_3 decrease in 1997 extends as high (~650 K) as is typical in the southern hemisphere (SH) and, as noted by M96 for 1995-96, the change was ~2/3 that typical in the SH for a similar period. However, Fig. 3 shows nearly all of the observed lower stratospheric O_3 loss during these NH winters, whereas in the SH O_3 loss may continue for a month after the spring equinox. In 1997, extra-vortex O_3 also decreased in the lower stratosphere (also seen in Fig. 1). Behavior like this has not been seen in any previous winters observed by MLS.

Fig. 2c shows time variations of $ColO_3$ in the Arctic low-$ColO_3$ region, as detailed above. Averages within the 210 K temperature contour at 46 hPa or even within a 465 K PV contour (although, as shown in Fig. 1, $ColO_3$ is not well correlated with the lower stratospheric vortex, and this average includes some very high $ColO_3$ values) show similar trends. $ColO_3$ in 1995-96 was lower than in the other years observed by MLS, including 1996-97. This is probably due mainly to the meteorological situation in 1995-96 [M96], when low temperatures were frequently along the vortex edge, and upper tropospheric blocking events were common, dynamical conditions that frequently lead to unusually low column O_3 [e.g., *Petzoldt et al.*, 1994 and references therein]. In contrast to other years, $ColO_3$ in Jan-Mar 1996 and Feb-Apr 1997 exhibited downward trends, when dynamical effects were expected to produce overall increasing trends. In Fig. 1, for example, a decrease between 28 Jan and 26 Feb 1997 is qualitatively consistent with the decrease in temperature, but the decrease between 26 Feb and 10 Apr 1997 would not have been expected given the considerable temperature increase. The downward trend in 1997 was ~1.25 times that in 1996, consistent with the expectation that O_3 loss over a larger vertical range (Fig. 3) would have a greater effect on $ColO_3$.

Fig. 4 shows MLS zonal-mean $ColO_3$, for high latitude (60-80°N) and mid-latitude (30-60°N) bands for 1991-1997. Interannual variability in zonal-mean MLS $ColO_3$ is generally consistent with what we see in zonal means (not shown) of TOMS total O_3, based on 1991-93 Nimbus-7, 1993-96 Meteor-3 and 1996-97 ADEOS TOMS data. Variations in NH column O_3 at higher latitudes are greatest during winter, with changes in zonal-means also reflecting differences in the position and size of the region of low column O_3 at high latitudes. $ColO_3$ was similar in all years in summer and early fall (June through October). High-latitude $ColO_3$ in Apr 1997 stands out as much lower than other springtime MLS observations. Unlike previous years, the lower stratospheric vortex was still strong, with low O_3 resulting from chemical loss confined within it (Fig. 1). A well-defined region of low temperatures at high latitudes persisted until about 20 Apr 1997 (vestiges of this can be seen on 24 Apr 1997, Fig. 1); since low temperatures are associated with low column O_3 [*Petzoldt et al.*, 1994 and references therein], this unusual dynamical situation also favored lower column O_3. MLS high-latitude $ColO_3$

increased rapidly in late April (see also Fig. 2c), concurrent with a rapid temperature increase and the breakdown of winter-like temperature patterns (Fig. 1). The increasing asymmetry of the polar low-$ColO_3$ region (Fig. 1) also implies that zonal means include more of a mixture of high and low values. Nearly all of the interannual and temporal differences in high latitude $ColO_3$ result from differences in the layer between 100 hPa and 22 hPa (not shown). Since lower stratospheric O_3 mixing ratios were not increasing significantly at this time and the O_3-depleted air remained confined inside a strong vortex (Figs. 1, 2a, 2b), much of the increase in $ColO_3$ must be due to dynamical effects associated with the increasing temperatures and belated transition to summer-like temperature patterns (warm polar regions).

In mid-latitudes (Fig. 4b) during February through April, $ColO_3$ was lower in 1997 than in 1996, nearly as low as in 1993, when low mid-latitude values are thought to have resulted from effects of the Mt. Pinatubo eruption [e.g., *Solomon et al.,* 1996 and references therein]. The two-year pattern of high/low mid-latitude $ColO_3$ may be related to the quasi-biennial oscillation [e.g., *Zawodny and McCormick,* 1991]. The increasing asymmetry of $ColO_3$ (Fig. 1) probably contributes to the mid-latitude decrease in late April as well as the contemporaneous high-latitude $ColO_3$ increase.

Summary

MLS observed O_3 loss in the Arctic vortex beginning in Jan 1997 at 585 K (~25 hPa) and in Feb 1997 at 465 K (~50 hPa). Compared to the low O_3 mixing ratios observed in 1995-96 [M96], vortex-averaged lower stratospheric O_3 was higher in Feb 1997, due to a later onset of low temperatures and chemical processing [S97]. The decrease in 1996-97 filled the vortex less completely than in 1995-96 at a given level, but the vertical extent of O_3 loss and the maximum local decrease were larger in 1996-97. Transport calculations indicate that masking of chemical O_3 loss by replenishment through diabatic descent was less in Feb 1997 than in Feb 1996, and that minimum lower stratospheric O_3 mixing ratios during the 1996-97 winter were never as low as those in 1995-96. Although O_3 loss continued later in 1996-97, it also began later, resulting in more O_3 at the beginning of the period of depletion. MLS column O_3 above 100 hPa in the confined region of low column 03 at high latitudes showed a stronger decreasing trend in 1996-97 than in 199,5-96, consistent with the larger vertical extent of the O_3 decrease. Unusually small values of high-latitude zonal-mean MLS column O_3 above 100 hPa in Apr 1997 resulted partly from chemical loss, but were closely related to the unusually late persistence of winter-like temperature patterns and a confined polar vortex.

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References

Coy, L., et al., Meteorology of the polar vortex: March 1997, *Geophys. Res. Lett., this issue*, 1997.

Donovan, D. P., Ozone, column ClO, and PSC measurements made at the NDSC Eureka observatory (80°N, 86°W) during the spring of 1997, *Geophys. Res. Lett., this issue*, 1997.

Froidevaux, L., et al., Validation of UARS MLS Ozone Measurements, *J. Geophys. Res., 101*, 10,017-10,060, 1996.

Manney G. L., et al., The anomalous Arctic lower stratospheric polar vortex of 1992-1993, *Geophys. Res. Lett., 21*, 2'105-2408, 1994.

Manney, G. L., et al., Polar vortex conditions during the 1995-96 Arctic winter: Meteorology and MLS ozone, *Geophys. Res. Lett., 23, 3'203-3206*, 1996.

Müller, R., et al., HALOE observations of chlorine activation and ozone depletion in the Arctic vortex in 1996-97, *Geophys. Ales. Lett., this issue*, 1997.

Petzoldt, K., et al., (correlation between stratospheric temperature, total ozone, and tropospheric weather systems, *Geophys. Res. Lett., 21*, 1203-1206, 1994.

Pierce, R. B., et al., HALOE observations of the Arctic vortex during the 1997 spring, *Geophys. Res. Lett., this issue*, 1997.

Santee, M. L., et al., MLS observations of HNO_3 and ('lo in tile 1996-97 Arctic polar vortex, *Geophys. Res. Lett., this issue*, 1 997.

Solomon, S., et al., The role of aerosol variations in anthropogenic ozone depletion at northern midlatitudes, *J. Geophys. Res.*, 101, 6713-6727, 1996.

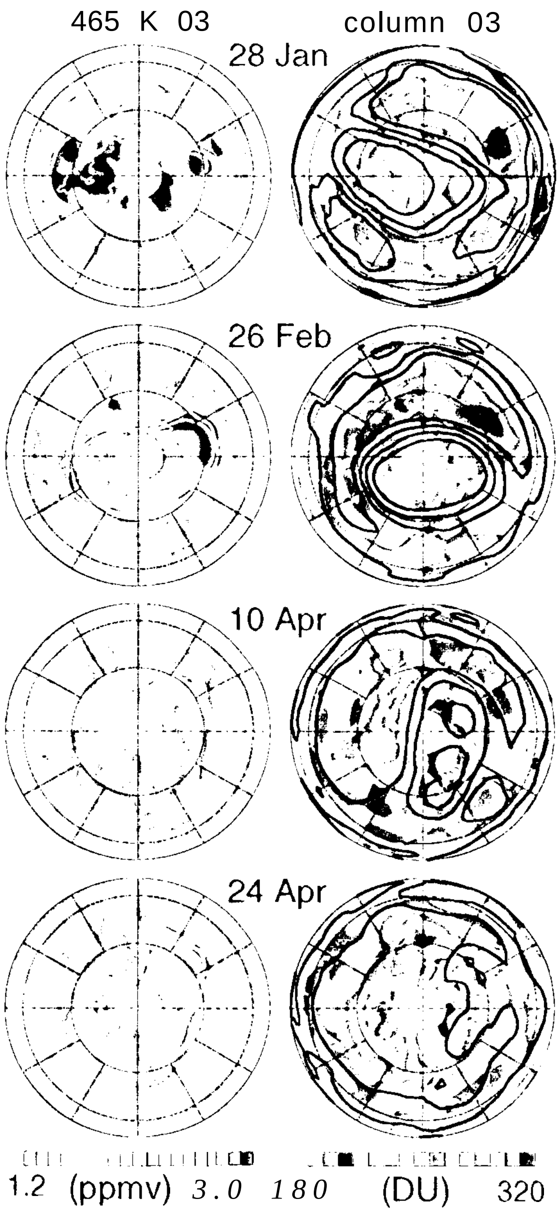
Zawodny, J. M., and M. P. McCormick, Stratospheric Aerosol and Gas Experiment II Measurements of the quasi-biennial oscillations in ozone and nitrogen dioxide. *J. Geophys. Res., 96*, 9371-9377, 1991.

Figure 1. 465 K MLS O_3, and MLS column O_3 above 100" hPa, on 28 Jan, 26 Feb, 10 Apr and 24 Apr 1997. Two PV contours in the region of strong gradients along the vortex edge are shown on the 465 K maps. 46 Ill's temperature contours of 200, 205, 210 and 215 K are overlaid on tile column O_3 maps. The projection is orthographic, with 0° at the bottom and 90°E to the right; dashed lines are 30° and 60°N.

Figure 2. (a) 585 K and (b) 465 K vortex-averaged O_3 (ppmv, averaged within the outermost of the two PV contours shown in Fig. 1), and (c) column O_3 above 100 hPa (DU, averaged poleward of 40° N for column $O_3 \leq 250$ DU), for 1 December to 30 April. Cyan triangles show 1995-96, magenta squares 1996-97, and previous UARS winters are shown as grey dots in the background. Thin magenta lines and small magenta dots show results of transport calculations and an estimate of minimum O_3 (see text).

Figure 3. MLS O_3 change (ppmv) over 69 days, between (a) 31 Jan and 10 Apr 1997, and (b) 25 Dec 1995 and 3 Mar 1996, in equivalent latitude/θ-space (see text).

Figure 4. Zonal mean (a) high-latitude (60° 80°N) and (b) mid-latitude (30° 60°N) MLS column O_3 above 100" III's, for 1991 through 1997.



465 K 03
column 03
28 Jan
26 Feb
10 Apr
24 Apr
1.2 (ppmv) 3.0
180 (DU) 320

Fig. 1

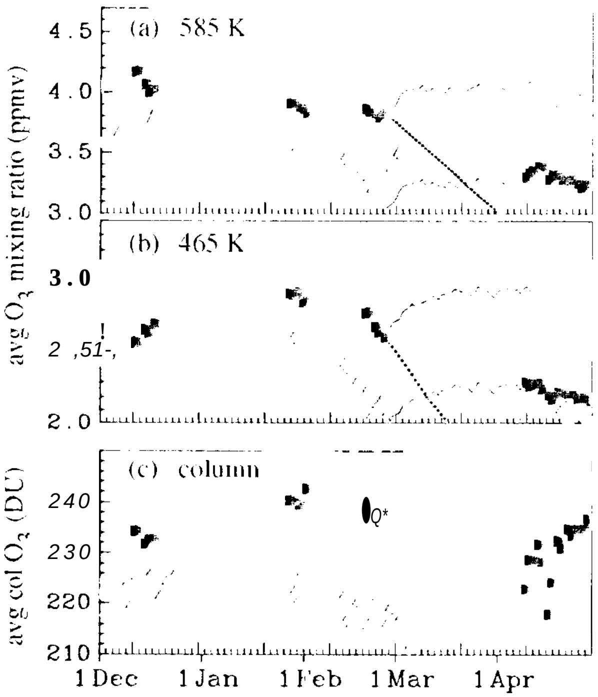

(a) 585 K
(b) 465 K
(c) column
avg O_3 mixing ratio (ppmv)
avg col O_3 (DU)
4.5
4.0
3.5
3.0
2.5
2.0
240
230
220
210
1 Dec
1 Jan
1 Feb
1 Mar
1 Apr

Fig. 2

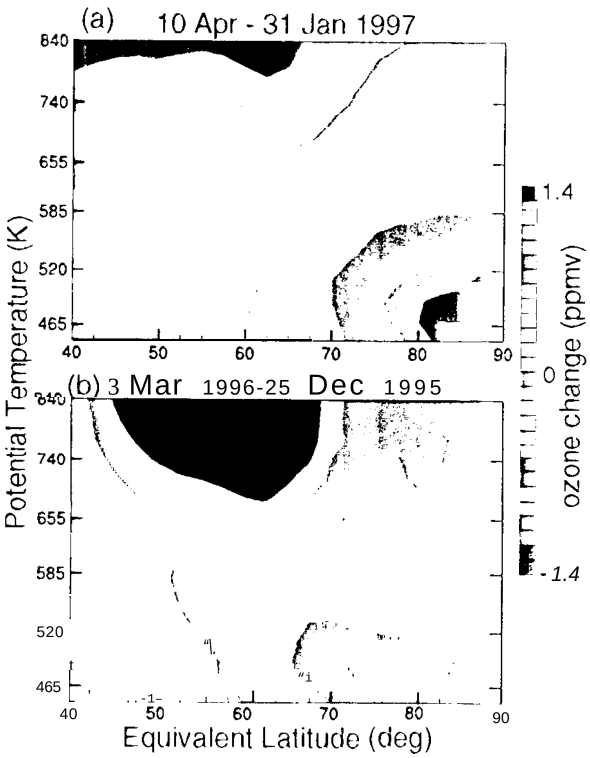

(a) 10 Apr - 31 Jan 1997
(b) 3 Mar 1996-25 Dec 1995
Potential Temperature (K)
Equivalent Latitude (deg)
ozone change (ppmv)
1.4
0
-1.4
840
740
655
585
520
465
40
50
60
70
80
90

Fig. 3

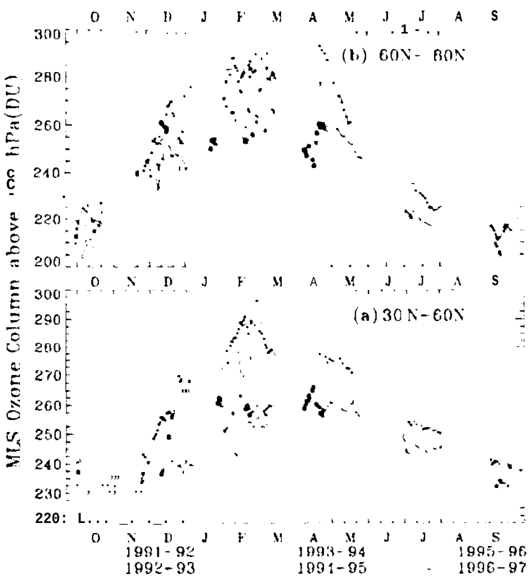

(b) 60N- 80N
(a) 30N-60N
MLS Ozone Column above 100 hPa(DU)
O N D J F M A M J J A S
1991-92
1992-93
1993-94
1994-95
1995-96
1996-97

Fig. 4